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INJECTIVITY AND PRODUCTIVITY ESTIMATION IN MULTIPLE FEED GEOTHERMAL WELLS

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ABSTRACT

A method is presented which allows individual zone injectivity/productivity to be determined without downhole flow measurements. Mass balance in conjunction with the specific pressure change measured at selected points in the the well is related to the individual zone injectivity/productivity which can then be used to estimate productive capacity. A sample staged completion test programme is presented to obtain the maximum information from a completed well without discharge or use of the downhole flow meter.

INTRODUCTION

Wells drilled in liquid-dominated geothermal fields may have large mass flow rates, high temperatures, and large amounts of dissolved solids. Discharge testing of some geothermal wells involving the disposal or reinjection of up to 50,000 m^3 of geothermal brine may have to await the installation of a complex array of surface equipment before testing can proceed. Even a brief vertical discharge of the well may be precluded due to thermal, noise or chemical pollution. In the Mokai field, New Zealand, a vertical discharge of well Mk5, at a mass flow rate of 200 kg/s and enthalpy about 1290 kJ/kg produced noise levels of over 120dBA near the wellhead. In order to obtain some measure of the productive or injective well capacity it is useful to determine individual permeable zone injectivity/productivity from injection tests which are not normally subject to the same environmental constraints as production tests.

BACKGROUND

Analysis of wellbore temperature and pressure profiles has taken on new significance with the development of downhole flow meters. These devices are able to provide the information required to confirm or refute previously held theories on the significance of specific profiles. Ironically this enabled the development of methods to determine permeable zone flow characteristics without using the flow meter.

Development of wellbore profile interpretation has proceeded rapidly since 1979. *Grant* (1979) showed how various pressure and temperature profiles could be produced in the wellbore depending on the phases present and flow occurring in the wellbore. *Stefansson and Steingrimsson* (1981) covered the application of various tools in geothermal well logging and interpretation techniques. *Dench* (1980) used measurements from the Olkaria geothermal field to show that pressures in the wellbore equalled the formation pressure only under specific constraints. *Horne* and *Castanada* (1981) used various temperature and pressure profiles to determine the existence of flows in the wellbore and locate selected permeable zones. *Bixley* and *Grant* (1981) presented a method to use pressure and temperature profiles to calculate individual permeable zone injectivity/productivity for a well with two dominant zones of permeability. The use of enthalpy balances and downhole chemistry in similar analyses is also discussed. *Grant et al.* (1982) presented data from a number of New Zealand geothermal fields showing linearity of formation pressure profiles in those that were liquid-dominated. *Grant et al.* (1983) discuss the identification of internal flows in the wellbore and the effect of these on pressure transients. *Gudmundsson* (1984) used a well with a single feed zone to demonstrate the use of the pressure pivot along with a wellbore simulator to predict the output curve.

The current study evolved from the need to determine individual permeable zone characteristics in Mokai well, Mk6, which contains six main permeable zones (*Leaver*, 1984). Staged completion testing had been undertaken in order to test temperature buildup techniques. During final completion testing the downhole flowmeter became inoperable necessitating the use of alternative techniques to calculate the required flow parameters.

CONCEPTUAL DEVELOPMENT

Instantaneous flow in a well is principally controlled by the location of permeable zones and the difference between the formation pressure profile and the flowing pressure profile. The difference between the two profiles determines both the magnitude and direction of the flow. Inherent assumptions are that the transmissivity (kh) and the viscosity (μ) are constant and that skin damage if present is the same at all permeable zones.

For *Darcy* flow in the formation:

$$q = -\frac{2\pi rkh}{\mu}\frac{\partial p}{\partial r} \tag{1}$$

For steady state horizontal flow, integrating Equation 1 between reference points 0 and 1 and assuming zero skin gives:

$$q = \frac{2\pi kh(p_1 - p_0)}{\mu\, ln(r_1/r_0)} \tag{2}$$

or

$$q \propto K(p_1 - p_0) \tag{3}$$

where

$$K = \frac{2\pi kh}{\mu\, ln(r_1/r_0)} \tag{4}$$

K may represent either the injectivity or productivity index depending on the direction of flow.

Figure 1 shows a schematic layout of typical pressure profiles during injection.

The *pivot point* is defined as the point at which the well pressure equals the formation pressure. From *Darcy's* Law for a single permeable zone of high transmissivity (kh) and low absolute flow rate (q), the pivot point will be located at the permeable zone as the difference between the well and formation pressures is small. For more than one feed zone the depth of the pivot point in the well will be determined by the permeability of each zone and the characteristics of the well and formation pressure profiles.

In Zone A of Figure 1 permeable zones above the pivot point will produce brine into the well during surface injection. Conversely injected fluid will flow into the formation in those permeable zones below the pivot point.

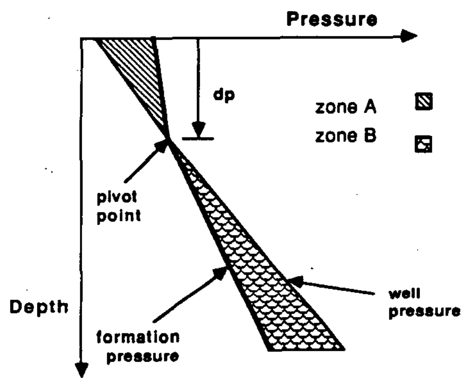

FIGURE 1: Schematic of typical pressure profiles.

MATHEMATICAL DEVELOPMENT

Principal assumptions used are:

(i) Radial *Darcy* flow in a homogeneous isotropic medium.

(ii) Incompressible fluid and formation.

(iii) Negligible thermal interaction effects such as condensation of vapour and contraction of the formation during injection.

Three cases are considered in the development of a general formula:

Case I---Single Permeable Zone

Consider a well with a permeable zone at location 1 in Figure 2. If the pressure gauge is located at the same depth as the permeable zone the injectivity is determined from the relation:

$$I_1 = \frac{\Delta q_s}{\Delta p_{w1}} \tag{5}$$

where

$$\Delta p_{w1} = p_{w1} - p_{f1} \tag{6}$$

If the pressure change is measured at some arbitrary depth, d_g, then a different overall injectivity will be measured.

$$I_0 = \frac{\Delta q_s}{\Delta p_{wg}} \tag{7}$$

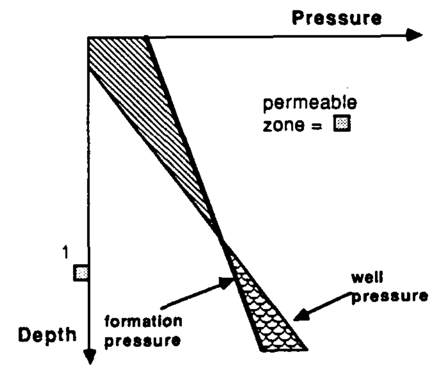

FIGURE 2: Single permeable zone in a geothermal well.

Substituting for Δq_s from Equation 5 gives:

$$I_1 = I_0 \frac{\Delta p_{wg}}{\Delta p_{w1}} \tag{8}$$

Case II---Double Permeable Zone Well

Consider a well with permeable zones at locations 1 and 2 in Figure 3. For this case the individual zone permeabilities cannot be directly calculated as the pressure profile in the well is determined by the equilibrium between the two permeable zones.

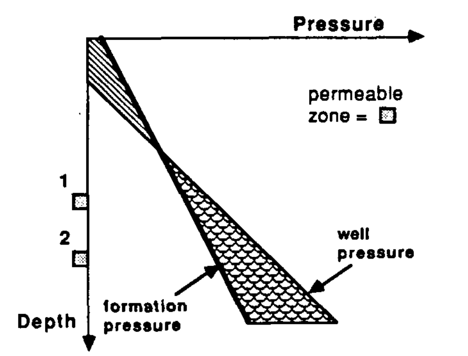

FIGURE 3: Double permeable zone configuration in a geothermal well.

The overall injectivity can be measured as for case I.

$$I_0 = \frac{\Delta q_s}{\Delta p_{wg}} \tag{9}$$

The individual zone injectivities are:

$$I_1 = \frac{\Delta q_1}{\Delta p_{w1}} \quad \text{and} \quad I_2 = \frac{\Delta q_2}{\Delta p_{w2}} \tag{10}$$

From conservation of mass

$$\Delta w_s = \Delta w_1 + \Delta w_2 \tag{11}$$

or

$$\frac{\Delta q_s}{v_s} = \frac{\Delta q_1}{v_1} + \frac{\Delta q_2}{v_2} \tag{12}$$

Eliminating flow terms using Equations 9, 10 in 12 gives:

$$\frac{I_0\, \Delta p_{wg}}{v_s} = \frac{I_1\, \Delta p_{w1}}{v_1} + \frac{I_2\, \Delta p_{w2}}{v_2} \tag{13}$$

Rearranging:

$$I_0 = \frac{\dfrac{I_1\, \Delta p_{w1}}{v_1} + \dfrac{I_2\, \Delta p_{w2}}{v_2}}{\dfrac{\Delta p_{wg}}{v_s}} \tag{14}$$

Since this equation has two unknowns I_1 and I_2 a second equation is required which is obtained by measuring the well pressure for a second step in flow rate. This equation will be identical in form to Equation 14.

Case III---General Case

Consider the case of a well with $n+m$ permeable zones with productivities, J_i , and injectivities, I_j , where there are n permeable zones above the *pivot point* and m permeable zones below the *pivot point* (Figure 4). Using induction from the previous two cases gives:

$$I_0 = \frac{\sum_{j=1}^{m} \dfrac{I_j \Delta p_{wj}}{v_j} - \sum_{i=1}^{n} \dfrac{J_i \Delta p_{wi}}{v_i}}{\dfrac{\Delta p_{wg}}{v_s}} \tag{15}$$

$n+m$ flow rate steps are required to uniquely determine the individual zone productivities (J_i) and injectivities (I_j). Furthermore pressure differences (Δp_w) must be calculated opposite each permeable zone in order to solve Equation 15.

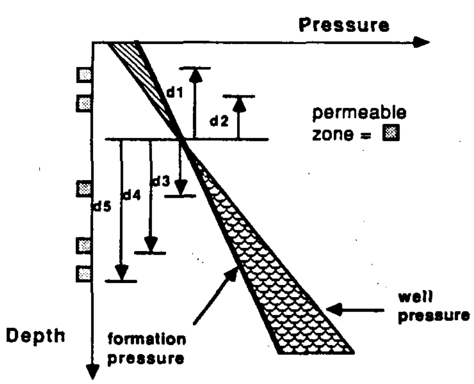

FIGURE 4: Multiple permeable zone configuration in a geothermal well.

In liquid dominated geothermal fields the number of pressure measurements required can be reduced by using the characteristic of these systems that the formation pressure profiles are linear with depth (*Grant et al.*, 1982). During water injection the well pressures below the water surface are also near linear with depth. This necessarily assumes:

(i) Flows from the formation into the well during injection do not significantly affect the overall density of the fluid column in the well.

(ii) Frictional flow effects in the wellbore are small.

(iii) Heat transfer from the formation to the wellbore fluid is small.

Once linearity of the pressure profiles has been established the geometry of the profiles can be used to modify Equation 15 so that only the permeable zone depths need be known along with two pressure measurements in order to establish the pressure change at each permeable zone.

By similar triangles from Figure 2:

$$\left[\frac{\Delta p_{wi}}{|d_p - d_i|}\right]_{i=1,n} = \left[\frac{\Delta p_{wj}}{|d_p - d_j|}\right]_{j=1,m} = \frac{\Delta p_{wg}}{|d_p - d_g|} \tag{16}$$

substituting from Equation 16 in 15 for Δp_{wi}, Δp_{wj} gives:

$$I_0 = \frac{\sum_{j=1}^{m} \dfrac{I_j\, |d_p - d_j|}{v_j} - \sum_{i=1}^{n} \dfrac{J_i\, |d_p - d_i|}{v_i}}{\dfrac{|d_p - d_g|}{v_s}} \tag{17}$$

DISCUSSION

Equations 16 and 17 require $n+m$ step changes in flow rate for each permeable zone injectivity/productivity to be uniquely determined. The number of flow rate step changes required is reduced by one for each permeable zone whose injectivity/productivity can be determined independently. If the upper permeable zones are producing brine into the well during injection, enthalpy balance techniques in conjunction with the temperature and pressure profiles can be used to independently determine the injectivity/productivity of these zones.

The use of pressure profiles to determine permeable zone injectivity/productivity requires a knowledge of the depth of the permeable zones, the specific volume of the formation fluid at each permeable level, and the stabilised pressure profiles at the required number of injection flow rates. The accurate location of feed zones and the effect of injected fluid on individual permeable zone characteristics are the principal limitations in application of the technique. An important feature is that no downhole flow measurements in the wellbore are required.

APPLICATION

Staged completion testing of a well enables the characteristics of some permeable zones to be determined during the drilling operation. Staged testing may cause delays during drilling of the well but this can be offset by the additional information obtained and by eliminating the need for extended testing on completion of the well at target depth.

The extent and type of testing undertaken will reflect the amount of information required from any single well. A flow chart is presented in Figure 5 to show how the following information could be obtained:

(i) Transmissivity, skin and under certain conditions productivity of the uppermost permeable zone.

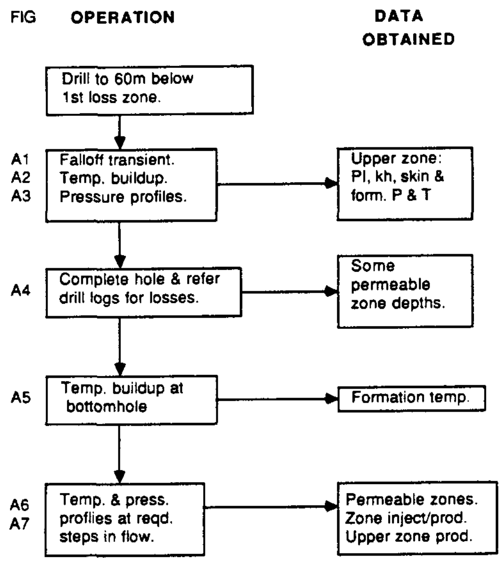

FIGURE 5: Flow chart for staged completion well testing

(ii) Formation pressures and temperatures.

(iii) Individual permeable zone injectivities.

A more detailed explanation of the techniques used to determine individual permeable zone flow characteristics from staged completion tests is given in Appendix A.

CONCLUSIONS

(1) Individual zone injectivity/productivity can be determined without the use of downhole flow measurements.

(2) Fewer pressure profile measurements are required where the formation and well pressure profiles are known to be linear with depth.

(3) Staged completion testing should be considered if in addition to the injectivity of each permeable zone, information on productivity, transmissivity and skin factor are required.

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NOTATION

d_g depth of gauge below surface
d_p depth of pivot point below surface
h formation thickness
I injectivity
I_0 overall injectivity calculated at d_g
J productivity
J_0 overall productivity calculated at d_g
k permeability
K proportionality constant in *Darcy's* Law
m number of permeable zones below the pivot point
n number of permeable zones above the pivot point
p pressure
p_f formation pressure
p_w well pressure
p_{wg} well pressure measured at gauge depth
q volumetric flow rate
q_s surface volumetric flow rate
r distance between source well and pressure point
t time
w_s surface mass flow rate
v specific volume
v_s surface specific volume
μ dynamic viscosity

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APPENDIX A

TYPICAL DATA FOR UPPER ZONE TESTING

A pressure falloff transient performed in conjunction with shutting the well in for temperature buildup measurements can provide an estimate of the formation pressure, skin, and transmissivity. The transient data may need to be constructed from a number of pressure profiles performed during buildup. Frequent linearity of pressure profiles during injection and warmup facilitate interpolating data to the permeable zone depth which may not be accurately known initially (Figure A1).

The method of *Roux et al.*(1979) can be used to obtain an estimate of the formation temperature (Figure A2).

For a single permeable zone pressure profiles measured at the start and end of the temperature buildup test may show a pivot which locates the permeable zone depth and provides an estimate of the formation pressure. Sudden inversions in the temperature profile due to cold drilling fluid in the formation can also indicate the permeable zone location. Depths over which the profile is constant may indicate internal flow in the wellbore (Figure A3).

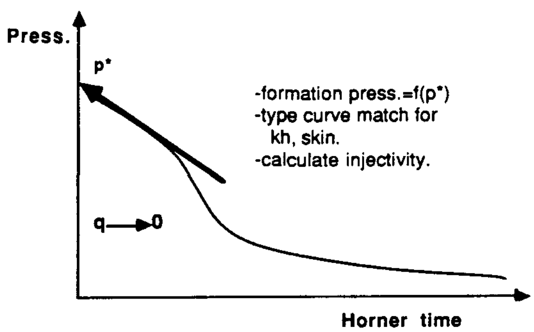

FIGURE A1: Pressure falloff transient.

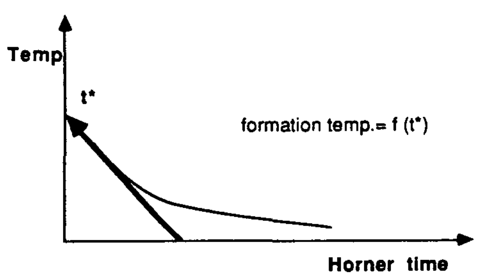

FIGURE A2: Temperature Buildup.

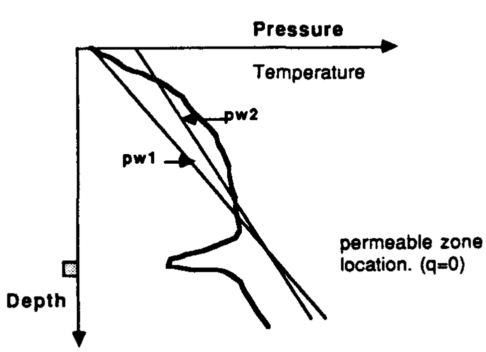

FIGURE A3: Pressure and temperature profiles during warmup.

TYPICAL DATA FOR COMPLETED WELL TESTING

Drilling logs can be used to determine permeable zone depths at which circulation losses occur (Figure A4).

A temperature buildup to determine bottomhole formation temperature is best performed immediately on well completion to reduce the time required to achieve acceptable results. Temperatures between the upper zone and bottomhole formation temperatures can be interpolated from a BPD or other applicable profile (Figure A5).

Injection into the well may cause upper zones to produce brine. By varying the flow rate, enthalpy balance techniques can be used to determine productivity at locations where temperature increases show the inflow of hot brine from permeable zones. Only the lowest of the permeable zones accepting injected fluid will be detectable using the bottomhole increase in temperature which reflects static bottomhole conditions below this lowest permeable zone (Figure A6).

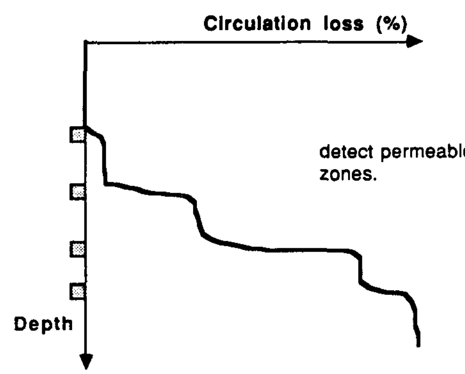

FIGURE A4: Permeable zone detection from circulation losses.

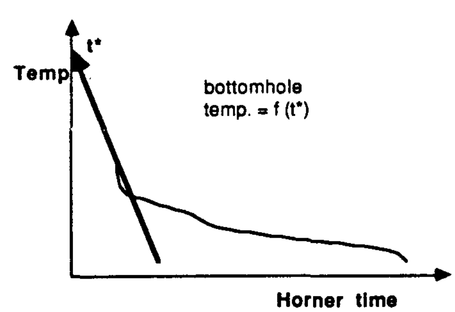

FIGURE A5: Bottomhole temperature buildup.

Individual zone injectivities can be determined by using step changes in the injected flow rate to produce the required number of different well pressure profiles (Figure A7).

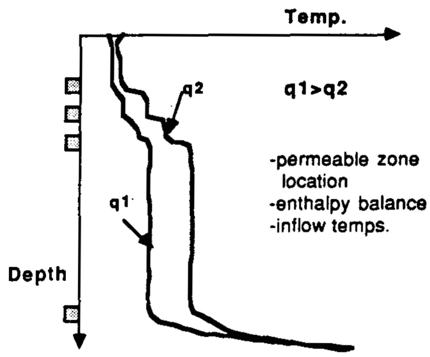

FIGURE A6: Temperature profile variation with flow rate.

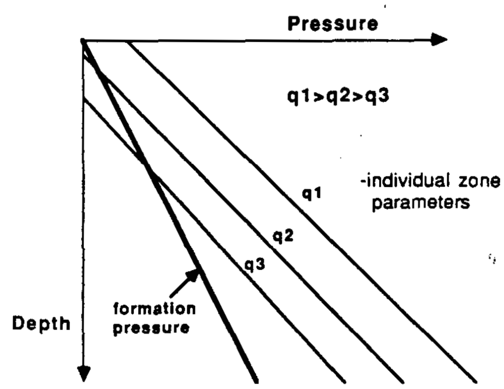

FIGURE A7: Pressure profile variation with flow rate.